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Top, GigaZ, MegaW *

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Abstract

We review the physics potential of top mass measurements and the GigaZ/MegaW options of the International Linear Collider (ILC) for probing New Physics models and especially the Minimal Supersymmetric Standard Model (MSSM). We demonstrate that the anticipated experimental accuracies at the ILC for the top-quark mass, m_t, the W boson mass, M_W, and the effective leptonic weak mixing angle, $\sin^2\theta_{\mathrm{eff}}$, will provide a high sensitivity to quantum effects of New Physics. In particular, a new and more precise measurement of $\sin^2\theta_{\mathrm{eff}}$, for which the experimental central value is currently obtained from an average where the most precise single measurements differ by more than three standard deviations, could lead to a situation where both the Standard Model and the MSSM in its most general form are ruled out. Alternatively, the precision measurements may resolve virtual effects of SUSY particles even in scenarios where the SUSY particles are so heavy that they escape direct detection at the LHC and the first phase of the ILC.

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We review the physics potential of top mass measurements and the GigaZ/MegaW options of the International Linear Collider (ILC) for probing New Physics models and especially the Minimal Supersymmetric Standard Model (MSSM). We demonstrate that the anticipated experimental accuracies at the ILC for the top-quark mass, m_t, the W boson mass, M_W, and the effective leptonic weak mixing angle, $\sin^2\theta_{\mathrm{eff}}$, will provide a high sensitivity to quantum effects of New Physics. In particular, a new and more precise measurement of $\sin^2\theta_{\mathrm{eff}}$, for which the experimental central value is currently obtained from an average where the most precise single measurements differ by more than three standard deviations, could lead to a situation where both the Standard Model and the MSSM in its most general form are ruled out. Alternatively, the precision measurements may resolve virtual effects of SUSY particles even in scenarios where the SUSY particles are so heavy that they escape direct detection at the LHC and the first phase of the ILC.

1 Introduction

Electroweak precision observables (EWPO) are a very powerful tool for testing the Standard Model (SM) and extensions of it. A particularly attractive extension is the Minimal Supersymmetric Standard Model (MSSM), see Ref. [1] for a review of electroweak precision physics in the MSSM. In this context the Z-pole observables and W boson physics play an important role. The most sensitive observables are the effective leptonic weak mixing angle, $\sin^2\theta_{\mathrm{eff}}$, and the W boson mass, M_W. Performing fits in constrained supersymmetric (SUSY) models a certain preference for not too heavy SUSY particles has been found [2–5], see Ref. [6] for other approaches; a detailed list of references can be found in Ref. [4]. The prospective improvements in the experimental accuracies, in particular at the ILC with GigaZ option (high luminosity running at the Z pole) and the MegaW option (high luminosity running at the WW threshold), will provide a high sensitivity to deviations both from the SM and the MSSM. In Tab. 1 we summarize the current experimental results [7–9] together with the anticipated improvements at the LHC and the ILC with GigaZ option, see Refs. [1, 10–12] for details.

The mass of the top quark, m_t, is a fundamental parameter of the electroweak theory. It is by far the heaviest of all quark masses and it is also larger than the masses of all other known fundamental particles. It is evident that a comprehensive program of high-precision measurements at the top threshold will have to be a key element in the physics program of a future Linear Collider. The top quark is deeply connected to many other issues of high-energy physics:

- The top quark could play a special role in/for electroweak symmetry breaking.
- The experimental uncertainty of m_t induces the largest parametric uncertainty in the prediction for electroweak precision observables [13] and can thus obscure new physics effects.

observable	central exp. value	$\sigma \equiv \sigma^{\rm today}$	$\sigma^{\rm LHC}$	$\sigma^{\rm ILC}$
M_W [GeV]	80.399	0.023	0.015	0.007
$\sin^2\theta_{\rm eff}$	0.23153	0.00016	0.00020–0.00014	0.000013
m_t [GeV]	173.3	1.1	1.0	0.1

Table 1: Summary of the electroweak precision observables, including the top-quark mass, their current experimental central values and experimental errors, $\sigma \equiv \sigma^{\rm today}$ [7–9]. Also shown are the anticipated experimental accuracies at the LHC, $\sigma^{\rm LHC}$, and the ILC (including the GigaZ/MegaW options), $\sigma^{\rm ILC}$. Each number represents the combined results of all detectors and channels at a given collider, taking into account correlated systematic uncertainties, see Refs. [1, 10–12] for details.

- In supersymmetric (SUSY) models the top quark mass is an important input parameter and is crucial for radiative electroweak symmetry breaking and unification.

- Little Higgs models contain “heavier tops”.

The calculations for $e^+e^- \to t\bar{t}$ at the threshold are quite advanced. This includes NNLO and NNNLO predictions as well as renormalization group improved NRQCD calculations, see e.g. Ref. [14] for a review. Also for the process $e^+e^- \to t\bar{t}H$ and the determination of the top Yukawa coupling substantial progress has been made recently, see e.g. Ref. [15].

The large value of m_t gives rise to a large coupling between the top quark and the Higgs boson and is furthermore important for flavor physics. It could therefore provide a window to new physics. (The correct prediction of m_t will be a crucial test for any fundamental theory.) The top-quark mass also plays an important role in electroweak precision physics, as a consequence in particular of non-decoupling effects being proportional to powers of m_t. A precise knowledge of m_t is therefore indispensable in order to have sensitivity to possible effects of new physics in electroweak precision tests.

The current world average for the top-quark mass from the measurement at the Tevatron is $m_t = 173.3 \pm 1.1$ GeV [16]. The prospective accuracy at the LHC is $\delta m_t^{\rm exp} = 1$ GeV [17], while at the ILC a very precise determination of m_t with an accuracy of $\delta m_t^{\rm exp} \lesssim 100$ MeV will be possible [18, 19]. This error contains both the experimental error of the mass parameter extracted from the $t\bar{t}$ threshold measurements at the ILC and the envisaged theoretical uncertainty from its transition into a suitable short-distance mass (like the $\overline{\rm MS}$ mass).

2 Top quark mass measurement at the ILC and its implications

In the following we show for some examples that in many physics applications the experimental error on m_t achievable at the LHC would be the limiting factor, demonstrating the need for the ILC precision. More examples can be found in Ref. [13].

2.1 The top quark mass and electroweak precision observables

In order to confront the predictions of supersymmetry (SUSY) with the electroweak precision data and to derive constraints on the supersymmetric parameters, it is desirable to achieve the same level of accuracy for the SUSY predictions as for the SM. In Refs. [20, 21] an evaluation of M_W and the Z-pole observables in the MSSM has been presented. It includes the full one-loop result (for the first time with the full complex phase dependence), all available MSSM two-loop corrections (entering via the ρ parameter [22–24]), as well as the full SM results, see Refs. [20, 21] for details. The Higgs-boson sector has been implemented including higher-order corrections (as evaluated with `FeynHiggs` [25–28]).

In addition to the experimental uncertainties, summarized in Tab. 1, there are two sources of theoretical uncertainties: those from unknown higher-order corrections ("intrinsic" theoretical uncertainties), and those from experimental errors of the input parameters ("parametric" theoretical uncertainties). The current and estimated future intrinsic uncertainties within the SM are [10, 29]

$$\Delta M_W^{\text{intr,today,SM}} \approx 4 \text{ MeV}, \qquad \Delta \sin^2\theta_{\text{eff}}^{\text{intr,today,SM}} \approx 5 \times 10^{-5} , \tag{1}$$

$$\Delta M_W^{\text{intr,future,SM}} \approx 2 \text{ MeV}, \qquad \Delta \sin^2\theta_{\text{eff}}^{\text{intr,future,SM}} \approx 2 \times 10^{-5} , \tag{2}$$

while in the MSSM the current intrinsic uncertainties are estimated to [1, 23, 24]

$$\Delta M_W^{\text{intr,today,MSSM}} \approx (5-9) \text{ MeV}, \quad \Delta \sin^2\theta_{\text{eff}}^{\text{intr,today,MSSM}} \approx (5-7) \times 10^{-5} , \tag{3}$$

depending on the supersymmetric (SUSY) mass scale. In the future one expects that they can be brought down to the level of the SM, see Eq. (2).

The parametric errors of M_W and $\sin^2\theta_{\text{eff}}$ induced by the top quark mass, the uncertainty of $\Delta\alpha_{\text{had}}$ (we assume a future determination of $\delta(\Delta\alpha_{\text{had}}) = 5 \times 10^{-5}$ [30]) and the experimental uncertainty of the Z boson mass, $\delta M_Z = 2.1$ MeV, are collected in Tab. 2.

	$\delta m_t = 1$ GeV	$\delta m_t = 0.1$ GeV	$\delta(\Delta\alpha_{\text{had}})$	δM_Z
$\delta \sin^2\theta_{\text{eff}}$ $[10^{-5}]$	3	0.3	1.8	1.4
ΔM_W [MeV]	6	1	1	2.5

Table 2: Parametric errors on the prediction of M_W and $\sin^2\theta_{\text{eff}}$.

In order to keep the theoretical uncertainty induced by m_t at a level comparable to or smaller than the other parametric and intrinsic uncertainties, δm_t has to be of $\mathcal{O}(0.1 \text{ GeV})$ in the case of M_W, and about 0.5 GeV in the case of $\sin^2\theta_{\text{eff}}$. If the experimental error of m_t remains substantially larger, it would constitute the limiting factor of the theoretical uncertainty. Using the EWPO to distinguish different models from each other or to determine indirectly the unknown model parameters, the ILC precision on m_t is crucial, in particular in view of the precision measurement of $\sin^2\theta_{\text{eff}}$ at GigaZ [13].

2.2 Top quark mass measurement and Higgs physics

Because of its large mass, the top quark is expected to have a large Yukawa coupling to Higgs bosons, being proportional to m_t. In each model where the Higgs boson mass is not a free parameter but predicted in terms of the the other model parameters (as e.g. in the MSSM), the diagram in Fig. 1 contributes to the Higgs mass. This diagram gives rise to a leading m_t contribution of the form

$$\Delta m_h^2 \sim G_F \; N_C \; C \; m_t^4 \; , \tag{4}$$

where G_F is the Fermi constant, N_C is the color factor, and the coefficient C depends on the specific model. Thus the experimental error of m_t necessarily leads to a parametric error in the Higgs boson mass evaluation.

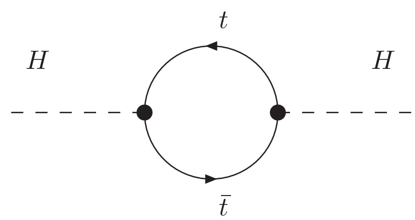

Figure 1: Loop contribution of the top quark to the Higgs boson mass.

Taking the MSSM as a specific example (including also the scalar top contributions and the appropriate renormalization) $N_C\, C$ is given for the light $\mathcal{CP}$-even Higgs boson mass in leading logarithmic approximation by

$$N_C\, C = \frac{3}{\sqrt{2}\,\pi^2\,\sin^2\beta}\;\log\left(\frac{m_{\tilde{t}_1} m_{\tilde{t}_2}}{m_t^2}\right) \; . \tag{5}$$

Here $m_{\tilde{t}_{1,2}}$ denote the two masses of the scalar tops. The optimistic LHC precision of $\delta m_t = 1$ GeV leads to an uncertainty of $\sim 2.5\%$ in the prediction of m_h, while the ILC will yield a precision of $\sim 0.2\%$. These uncertainties have to be compared with the anticipated precision of the future Higgs boson mass measurements. With a precision of $\delta m_h^{\rm exp,LHC} \approx$ 0.2 GeV [31, 32] the relative precision is at the level of $\sim 0.2\%$. It is apparent that only the ILC precision of m_t will yield a parametric error small enough to allow a precise comparison of the Higgs boson mass prediction and its experimental value.

Another issue that has to be kept in mind here (in SUSY as in any other model predicting m_h) is the intrinsic theoretical uncertainty due to missing higher-order corrections. Within the MSSM currently this uncertainty is estimated to $\delta m_h^{\rm intr,today} \approx 3$ GeV [1, 27][1]. This uncertainty could go down by $\sim$ 1 GeV once the recent three-loop corrections obtained in Ref. [33] will be included. In the future one can hope for an improvement down to $\lesssim 0.5$ GeV or better [1, 34], i.e. with sufficient effort on higher-order corrections it should be possible to reduce the intrinsic theoretical uncertainty to the level of $\delta m_h^{\rm exp,LHC}$.

Confronting the theoretical prediction of m_h with a precise measurement of the Higgs boson mass constitutes a very sensitive test of the MSSM (or any other model that predicts m_h), which allows one to obtain constraints on the model parameters. However, the sensitivity of the m_h measurement cannot directly be translated into a prospective indirect determination of a single model parameter. In a realistic situation the anticipated experimental errors of *all* relevant SUSY parameters have to be taken into account. For examples including these parametric errors see Refs. [13, 35].

[1] We are not aware of any such estimate in other New Physics models.

3 M_W and $\sin^2\theta_{\rm eff}$ in a global MSSM scan

The effective weak mixing angle is determined from various asymmetries and other EWPO as shown in Fig. 2 [36]. The world average for the effective weak mixing angle is

$$\delta \sin^2\theta_{\rm eff}^{\rm exp} = 0.23153 \pm 0.00016 \,, \tag{6}$$

with a χ^2/d.o.f of 11.8/5, corresponding to a probability of 3.7% [7, 36]. The large χ^2 is driven by the two single most precise measurements, $A_{\rm LR}^e$ by SLD and $A_{\rm FB}^b$ by LEP, corresponding to

$$A_{\rm FB}^b({\rm LEP}) : \sin^2\theta_{\rm eff}^{\rm exp,LEP} = 0.23221 \pm 0.00029 \,, \tag{7}$$
$$A_{\rm LR}^e({\rm SLD}) : \sin^2\theta_{\rm eff}^{\rm exp,SLD} = 0.23098 \pm 0.00026 \,. \tag{8}$$

The earlier (latter) one prefers a value of $M_{H^{\rm SM}} \sim 32(437)$ GeV [37]. The two measurements differ by more than $3\,\sigma$. The averaged value of $\sin^2\theta_{\rm eff}$, as shown in Fig. 2, prefers $M_{H^{\rm SM}} \sim$ 110 GeV [37].

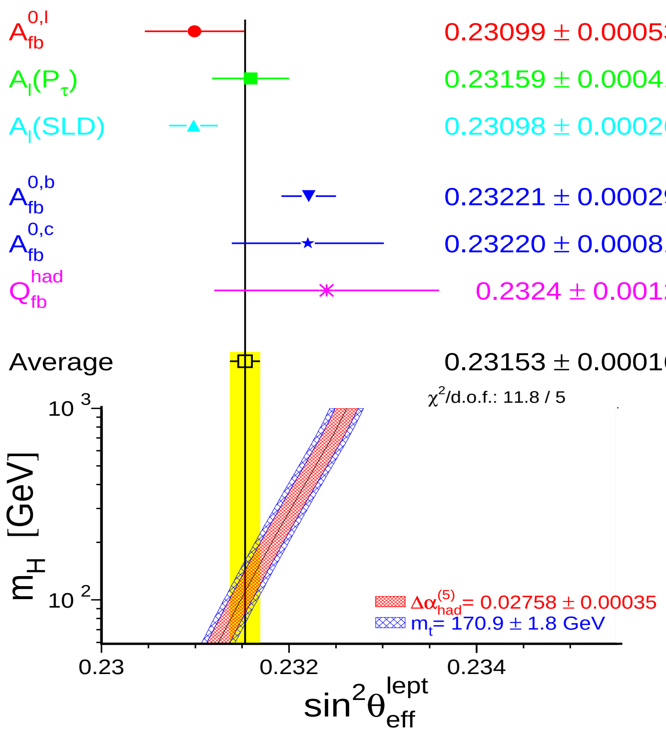

Figure 2: Individual measurements and world-average of $\sin^2\theta_{\rm eff}$. The experimental results are compared with the prediction within the SM as a function of $M_{H^{\rm SM}}$ for $m_t = 170.9 \pm 1.8$ GeV and $\Delta\alpha^5_{\rm had} = 0.02758 \pm 0.00035$ [36].

We now analyse the sensitivity of M_W and $\sin^2\theta_{\rm eff}$ to higher-order effects in the MSSM by scanning over a broad range of the SUSY parameter space. The following SUSY parameters are varied independently of each other in a random parameter scan within the given range:

$$\begin{aligned}
\text{sleptons} &: \quad M_{\tilde{F},\tilde{F}'} = 100\ldots2000\text{ GeV},\\
\text{light squarks} &: \quad M_{\tilde{F},\tilde{F}'_{\text{up/down}}} = 100\ldots2000\text{ GeV},\\
\tilde{t}/\tilde{b}\text{ doublet} &: \quad M_{\tilde{F},\tilde{F}'_{\text{up/down}}} = 100\ldots2000\text{ GeV},\quad A_{\tau,t,b} = -2000\ldots2000\text{ GeV},\\
\text{gauginos} &: \quad M_{1,2} = 100\ldots2000\text{ GeV},\quad m_{\tilde{g}} = 195\ldots1500\text{ GeV},\\
&\quad\;\; \mu = -2000\ldots2000\text{ GeV},\\
\text{Higgs} &: \quad M_A = 90\ldots1000\text{ GeV},\quad \tan\beta = 1.1\ldots60.
\end{aligned} \tag{9}$$

Here $M_{\tilde{F},\tilde{F}'}$ are the diagonal soft SUSY-breaking parameters in the sfermion sector, A_f denote the trilinear couplings, $M_{1,2}$ are the soft SUSY-breaking parameters in the chargino and neutralino sectors, $m_{\tilde{g}}$ is the gluino mass, μ the Higgs mixing parameter, M_A the $\mathcal{CP}$-odd Higgs boson mass, and $\tan\beta$ is the ratio of the two vacuum expectation values. Only the constraints on the MSSM parameter space from the LEP Higgs searches [38, 39] and the lower bounds on the SUSY particle masses from direct searches as given in Ref. [40] were taken into account. Apart from these constraints no other restrictions on the MSSM parameter space were made.

In Fig. 3 we compare the SM and the MSSM predictions for M_W and $\sin^2\theta_{\text{eff}}$ as obtained from the scatter data. The predictions within the two models give rise to two bands in the M_W–$\sin^2\theta_{\text{eff}}$ plane with only a relatively small overlap region (indicated by a dark-shaded (blue) area). The allowed parameter region in the SM (the medium-shaded (red) and dark-shaded (blue) bands) arises from varying the mass of the SM Higgs boson, from $M_{H^{\text{SM}}} = 114$ GeV, the LEP exclusion bound [39] (lower edge of the dark-shaded (blue) area), to 400 GeV (upper edge of the medium-shaded (red) area), and from varying m_t in the range of $m_t = 165\ldots175$ GeV. The light shaded (green) and the dark-shaded (blue) areas indicate allowed regions for the unconstrained MSSM. The decoupling limit with SUSY masses of $\mathcal{O}(2\text{ TeV})$ yields the upper edge of the dark-shaded (blue) area. Thus, the overlap region between the predictions of the two models corresponds in the SM to the region where the Higgs boson is light, i.e., in the MSSM allowed region ($M_h \lesssim 130$ GeV [27]). In the MSSM it corresponds to the case where all superpartners are heavy, i.e., the decoupling region of the MSSM.

The 68% C.L. experimental results for M_W and $\sin^2\theta_{\text{eff}}$ are indicated in the plot. The center ellipse corresponds to the current world average given in Eq. (6). Also shown are the error ellipses corresponding to the two individual main measurements of $\sin^2\theta_{\text{eff}}$ as given in Eqs. (7), (8). The anticipated improvement with the GigaZ/MegaW options, indicated as small ellipse, is shown around the current experimental central data. One can see that the current averaged value is compatible with the SM (favoring a light Higgs boson and a heavier top quark) and with the MSSM. The value of $\sin^2\theta_{\text{eff}}$ obtained from A_{LR}^e(SLD) clearly favors the MSSM over the SM. On the other hand, the value of $\sin^2\theta_{\text{eff}}$ obtained from A_{FB}^b(LEP) together with the M_W data from LEP and the Tevatron would correspond to an experimentally preferred region that deviates from the predictions of both models. Thus, the unclear experimental situation regarding the two single most precise measurements entering the combined value for $\sin^2\theta_{\text{eff}}$ has a significant impact on the constraints that can be obtained from this precision observable on possible New Physics scenarios. Measurements at a new e^+e^- Z factory, which could be realized in particular with the GigaZ option of the ILC, would be needed to resolve this issue. As indicated by the solid light shaded (red)

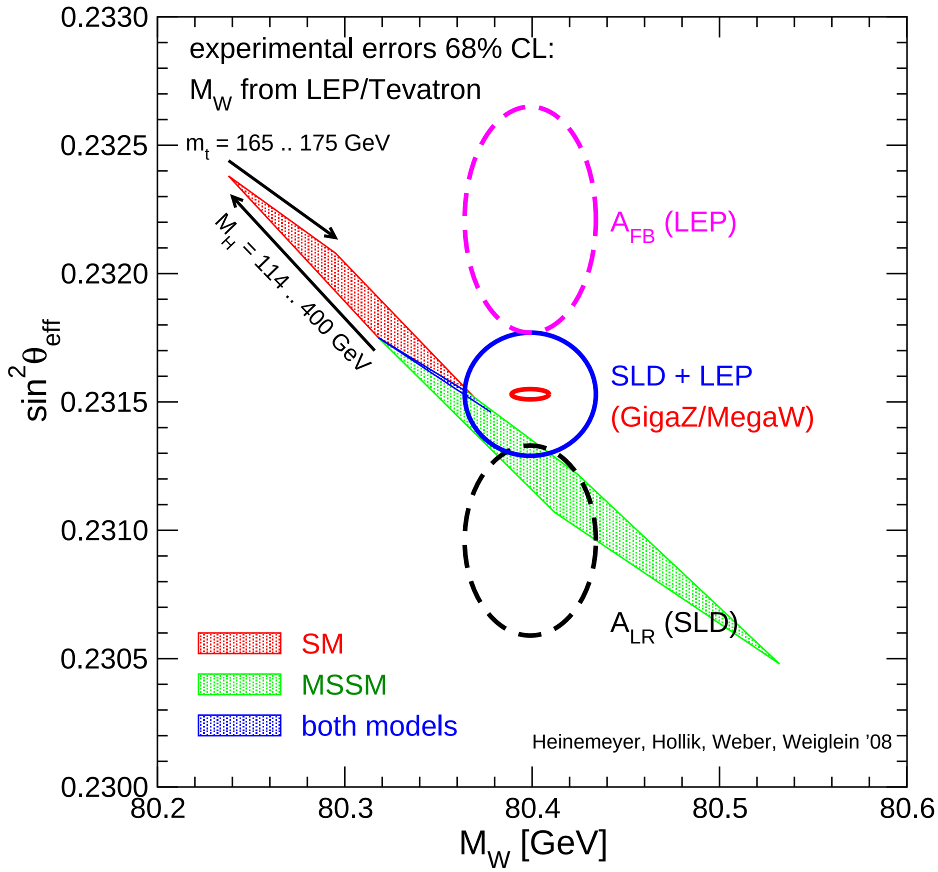

Figure 3: MSSM parameter scan for M_W and $\sin^2\theta_{\rm eff}$ over the ranges given in Eq. (9) with $m_t = 165\ldots175$ GeV. Todays 68% C.L. ellipses (from $A_{\rm FB}^b$(LEP), $A_{\rm LR}^e$(SLD) and the world average) are shown as well as the anticipated GigaZ/MegaW precisions, drawn around todays central value

ellipse, the anticipated GigaZ/MegaW precision of the combined M_W–$\sin^2\theta_{\rm eff}$ measurement could put severe constraints on each of the models and resolve the discrepancy between the $A_{\rm FB}^b$(LEP) and $A_{\rm LR}^e$(SLD) measurements. If the central value of an improved measurement with higher precision should turn out to be close to the central value favored by the current measurement of $A_{\rm FB}^b$(LEP), this would mean that the electroweak precision observables M_W and $\sin^2\theta_{\rm eff}$ could rule out both the SM and the most general version of the MSSM.

4 Scenario where no SUSY particles are observed at the LHC

It is interesting to investigate whether the high accuracy achievable at the GigaZ option of the ILC would provide sensitivity to indirect effects of SUSY particles even in a scenario where the (strongly interacting) superpartners are so heavy that they escape detection at the LHC.

We consider in this context a scenario with very heavy squarks and a very heavy gluino.

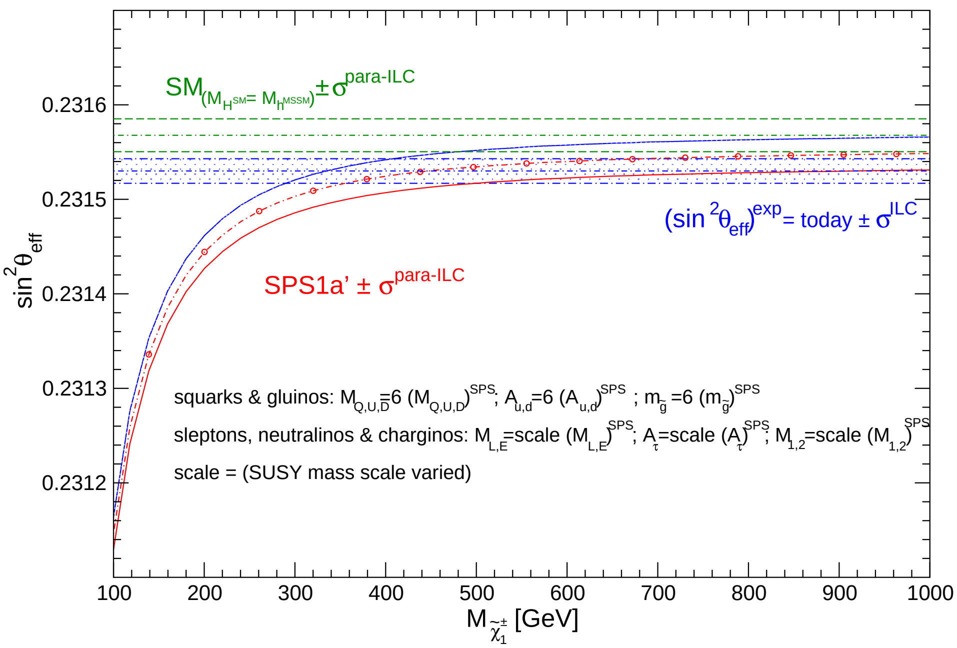

Figure 4: Theoretical prediction for $\sin^2\theta_{\rm eff}$ in the SM and the MSSM (including prospective parametric theoretical uncertainties) compared to the experimental precision at the ILC with GigaZ option. An SPS1a$'$ inspired scenario is used, where the squark and gluino mass parameters are fixed to 6 times their SPS 1a$'$ values. The other mass parameters are varied with a common scalefactor.

It is based on the values of the SPS 1a$'$ benchmark scenario [41], but the squark and gluino mass parameters are fixed to 6 times their SPS 1a$'$ values. The other masses are scaled with a common scale factor except M_A which we keep fixed at its SPS 1a$'$ value. In this scenario the strongly interacting particles are too heavy to be detected at the LHC, while, depending on the scale-factor, some color-neutral particles may be in the ILC reach. In Fig. 4 we show the prediction for $\sin^2\theta_{\rm eff}$ in this SPS 1a$'$ inspired scenario as a function of the lighter chargino mass, $m_{\tilde{\chi}_1^\pm}$. The prediction includes the parametric uncertainty, $\sigma^{\rm para-ILC}$, induced by the ILC measurement of m_t, $\delta m_t = 100$ MeV [19], and the numerically more relevant prospective future uncertainty on $\Delta\alpha^{(5)}_{\rm had}$, $\delta(\Delta\alpha^{(5)}_{\rm had}) = 5\times10^{-5}$ [30]. The MSSM prediction for $\sin^2\theta_{\rm eff}$ is compared with the experimental resolution with GigaZ precision, $\sigma^{\rm ILC} = 0.000013$, using for simplicity the current experimental central value. The SM prediction (with $M_{H^{\rm SM}} = M_h^{\rm MSSM}$) is also shown, applying again the parametric uncertainty $\sigma^{\rm para-ILC}$.

Despite the fact that no colored SUSY particles would be observed at the LHC in this scenario, the ILC with its high-precision measurement of $\sin^2\theta_{\rm eff}$ in the GigaZ mode could resolve indirect effects of SUSY up to $m_{\tilde{\chi}_1^\pm} \lesssim 500$ GeV. This means that the high-precision measurements at the ILC with GigaZ option could be sensitive to indirect effects of SUSY even in a scenario where SUSY particles have *neither* been directly detected at the LHC nor the first phase of the ILC with a centre of mass energy of up to 500 GeV.

5 Conclusions

EWPO provide a very powerful test of the SM and the MSSM. We have reviewed results for M_W and $\sin^2\theta_{\rm eff}$. The sensitivity to higher-order effects will drastically improve with the ILC precision (including the GigaZ/MegaW options) on the EWPO and m_t. This has been illustrated in three examples. A precise m_t determination is crucial

A general scan over the MSSM parameter space for $\sin^2\theta_{\rm eff}$ and m_t currently does not prefer the SM or the MSSM over the other. However, the anticipated GigaZ precision indicates the high potential for a significant improvement of the sensitivity of the electroweak precision tests. In a second example we have assumed a scenario with very heavy SUSY particles, outside the reach of the LHC and the first stage of the ILC with $\sqrt{s} = 500$ GeV. It has been shown that even in such a scenario the GigaZ precision on $\sin^2\theta_{\rm eff}$ may resolve virtual effects of SUSY particles, providing a possible hint to the existence of new physics.

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References

[1] S. Heinemeyer, W. Hollik and G. Weiglein, *Phys. Rept.* **425** (2006) 265 [arXiv:hep-ph/0412214].

[2] O. Buchmueller et al., *Phys. Lett.* **B 657** (2007) 87 [arXiv:0707.3447 [hep-ph]].

[3] O. Buchmueller et al., *JHEP* **0809** (2008) 117 [arXiv:0808.4128 [hep-ph]].

[4] O. Buchmueller et al., *Eur. Phys. J.* **C 64** (2009) 391 [arXiv:0907.5568 [hep-ph]].

[5] O. Buchmueller et al., *Phys. Rev.* **D 81** (2010) 035009. [arXiv:0912.1036 [hep-ph]].

[6] R. Lafaye, T. Plehn, M. Rauch and D. Zerwas, *Eur. Phys. J.* **C 54** (2008) 617 [arXiv:0709.3985 [hep-ph]];
F. Feroz, B. Allanach, M. Hobson, S. AbdusSalam, R. Trotta and A. Weber, *JHEP* **0810** (2008) 064 [arXiv:0807.4512 [hep-ph]];
R. Trotta, F. Feroz, M. Hobson, L. Roszkowski and R. Ruiz de Austri, *JHEP* **0812** (2008) 024 [arXiv:0809.3792 [hep-ph]];
P. Bechtle, K. Desch, M. Uhlenbrock and P. Wienemann, *Eur. Phys. J.* **C 66** (2010) 215 [arXiv:0907.2589 [hep-ph]];
M. Cabrera, A. Casas and R. Ruiz de Austri, *JHEP* **1005** (2010) 043 [arXiv:0911.4686 [hep-ph]].

[7] [The ALEPH, DELPHI, L3, OPAL, SLD Collaborations, the LEP Electroweak Working Group, the SLD Electroweak and Heavy Flavour Groups], *Phys. Rept.* **427** (2006) 257 [arXiv:hep-ex/0509008];
[The ALEPH, DELPHI, L3 and OPAL Collaborations, the LEP Electroweak Working Group], arXiv:hep-ex/0511027.

[8] See: `lepewwg.web.cern.ch/LEPEWWG/Welcome.html` .

[9] [Tevatron Electroweak Working Group], see: `tevewwg.fnal.gov` .

[10] U. Baur, R. Clare, J. Erler, S. Heinemeyer, D. Wackeroth, G. Weiglein and D. Wood, arXiv:hep-ph/0111314.

[11] J. Erler, S. Heinemeyer, W. Hollik, G. Weiglein and P. Zerwas, *Phys. Lett.* **B 486** (2000) 125 [arXiv:hep-ph/0005024.]

[12] R. Hawkings and K. Mönig, *EPJdirect* **C 8** (1999) 1 [arXiv:hep-ex/9910022].

[13] S. Heinemeyer, S. Kraml, W. Porod and G. Weiglein, *JHEP* **0309** (2003) 075 [arXiv:hep-ph/0306181].

[14] A. Hoang, *PoS* **TOP2006** (2006) 032 [arXiv:hep-ph/0604185].

[15] C. Farrell and A. Hoang, *Phys. Rev.* **D 74** (2006) 014008 [arXiv:hep-ph/0604166]; K. Kolodziej and S. Szczypinski, *Nucl. Phys.* **B 801** (2008) 153 [arXiv:0803.0887 [hep-ph]].

[16] Tevatron Electroweak Working Group and CDF Collaboration and D0 Collaboration, arXiv:1007.3178 [hep-ex].

[17] M. Beneke et al., arXiv:hep-ph/0003033.

[18] TESLA Technical Design Report [TESLA Collaboration] Part 3, "Physics at an e^+e^- Linear Collider", arXiv:hep-ph/0106315, see: `tesla.desy.de/new_pages/TDR_CD/start.html`; T. Abe et al., arXiv:hep-ex/0106055; K. Abe et al., arXiv:hep-ph/0109166.

[19] A. Hoang et al., *Eur. Phys. Jour.* **C 3** (2000) 1 [arXiv:hep-ph/0001286]; M. Martinez, R. Miquel, *Eur. Phys. Jour.* **C 27** (2003) 49 [arXiv:hep-ph/0207315].

[20] S. Heinemeyer, W. Hollik, D. Stockinger, A. Weber and G. Weiglein, *JHEP* **0608** (2006) 052 [arXiv:hep-ph/0604147].

[21] S. Heinemeyer, W. Hollik, A. Weber and G. Weiglein, *JHEP* **0804** (2008) 039 [arXiv:0710.2972 [hep-ph]].

[22] A. Djouadi, P. Gambino, S. Heinemeyer, W. Hollik, C. Jünger and G. Weiglein, *Phys. Rev. Lett.* **78** (1997) 3626 [arXiv:hep-ph/9612363]; *Phys. Rev.* **D 57** (1998) 4179 [arXiv:hep-ph/9710438].

[23] S. Heinemeyer and G. Weiglein, *JHEP* **0210** (2002) 072 [arXiv:hep-ph/0209305]; arXiv:hep-ph/0301062.

[24] J. Haestier, S. Heinemeyer, D. Stöckinger and G. Weiglein, *JHEP* **0512** (2005) 027 [arXiv:hep-ph/0508139]; arXiv:hep-ph/0506259.

[25] S. Heinemeyer, W. Hollik and G. Weiglein, *Comput. Phys. Commun.* **124** 2000 76 [arXiv:hep-ph/9812320]. The code is accessible via `www.feynhiggs.de` .

[26] S. Heinemeyer, W. Hollik and G. Weiglein, *Eur. Phys. J.* **C 9** (1999) 343 [arXiv:hep-ph/9812472].

[27] G. Degrassi, S. Heinemeyer, W. Hollik, P. Slavich and G. Weiglein, *Eur. Phys. J.* **C 28** (2003) 133 [arXiv:hep-ph/0212020].

[28] M. Frank, T. Hahn, S. Heinemeyer, W. Hollik, R. Rzehak and G. Weiglein, *JHEP* **0702** (2007) 047 [arXiv:hep-ph/0611326].

[29] M. Awramik, M. Czakon, A. Freitas, G. Weiglein, *Phys. Rev.* **D 69** (2004) 053006 [arXiv:hep-ph/0311148]; *Phys. Rev. Lett.* **93** (2004) 201805 [arXiv:hep-ph/0407317].

[30] F. Jegerlehner, talk presented at the LNF Spring School, Frascati, Italy, 1999, see: `www-com.physik.hu-berlin.de/ fjeger/Frascati99.ps.gz` ; arXiv:hep-ph/0105283.

[31] G. Aad et al. [The ATLAS Collaboration], "Expected Performance of the ATLAS Experiment - Detector, Trigger and Physics," arXiv:0901.0512 [hep-ex].

[32] G. Bayatian et al. [CMS Collaboration], *CMS Technical Design Report, Volume II: Physics Performance*, CERN-LHCC-2006-021, CMS-TDR-008-2 *J. Phys.* **G 34** (2007) 995; see: `cmsdoc.cern.ch/cms/cpt/tdr/` .

[33] S. Martin, *Phys. Rev.* **D 75** (2007) 055005 [arXiv:hep-ph/0701051]; R. Harlander, P. Kant, L. Mihaila and M. Steinhauser, *Phys. Rev. Lett.* **100** (2008) 191602 [*Phys. Rev. Lett.* **101** (2008) 039901] [arXiv:0803.0672 [hep-ph]]; arXiv:1005.5709 [hep-ph].

[34] S. Heinemeyer, *Int. J. Mod. Phys.* **A 21** (2006) 2659 [arXiv:hep-ph/0407244].

[35] G. Weiglein et al. [LHC/ILC Study Group], *Phys. Rept.* **426** (2006) 47 [arXiv:hep-ph/0410364]; A. De Roeck et al., *Eur. Phys. J.* **C 66** (2010) 525 [arXiv:0909.3240 [hep-ph]].

[36] M. Grünewald, arXiv:0709.3744 [hep-ex]; arXiv:0710.2838 [hep-ex].

[37] M. Grünewald, *priv. communication.*

[38] [LEP Higgs working group], *Eur. Phys. J.* **C 47** (2006) 547 [arXiv:hep-ex/0602042].

[39] [LEP Higgs working group], *Phys. Lett.* **B 565** (2003) 61 [arXiv:hep-ex/0306033].

[40] C. Amsler et al. [Particle Data Group], *Phys. Lett.* **B 667** (2008) 1.

[41] B. Allanach et al., *Eur. Phys. J.* **C 25** (2002) 113 [arXiv:hep-ph/0202233].